UV Opacity in Nearby Galaxies and Application to Distant Galaxies

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Abstract. The effects of dust opacity on the radiation of nearby and distant galaxies are reviewed. The geometrical distribution of the dust inside the galaxy plays a fundamental role in determining the wavelength dependence of the obscuration and the opacity of the galaxy. In the local Universe, late Hubble type galaxies appear to contain enough dust that corrections for the effect of obscuration become important. This is true expecially at blue and UV wavelengths, i.e. in the wavelength range of interest for studies of massive stars and star formation processes. Multiwavelength observations provide a powerful tool for characterizing the reddening caused by dust. A 'recipe' is given for removing the dust reddening and recovering the UV and optical light in star-forming galaxies.

OPACITY IN THE LOCAL AND DISTANT UNIVERSE

Dust opacity alters the radiation from astronomical sources and the physical quantities we derive from it. The effects of dust on the light are twofold: a) global dimming of the radiation output from a source and b) selective (i.e., wavelength-dependent) removal of the radiation. Because of the wavelength dependence of the extinction, the UV will be more affected by dust than the optical or the infrared; sources which are optically thin in the visible (e.g., A_V=0.3) become optically thick in the UV ($A_{1300\,\mathring{A}} \simeq 1$). Dust, therefore, can have a major effect on the wavelength range selected for studying high-mass star formation processes. Matters are further complicated by two additional "characteristics" of reddening:

• the details of the extinction curve are environment-dependent. The best known cases are the diffuse ISM extinction curves of the Milky Way (Seaton 1979), the Large Magellanic Cloud (LMC, Fitzpatrick 1986), the the Small Magellanic Cloud (SMC, Bouchet et al. 1985), and our twin galaxy M31 (Bianchi et al. 1996), which are characterized by different shapes. Even within our own Milky Way, different environments have different extinction

curves (Cardelli, Clayton & Mathis 1989).

• In extended objects (HII regions, galaxies, etc.) the 'effective' obscuration is a function of the geometrical distribution of the dust relative to the emitters (e.g., Witt, Thronson & Capuano 1992). An extinction curve can be defined or used in a straightforward manner only when all the dust is foreground to the emitter, as in the case of stars. In galaxies, the dust is usually mixed in a complicate fashion with the dust; geometry becomes the dominant factor in determining the wavelength dependence of the obscuration (Natta & Panagia 1984, Calzetti et al. 1994, CKS94 hereafter). Even in the simplest (unrealistic) case that all the dust is in a shell surrounding the galaxy, back-scattering from the farthest regions of the dust shell into the line of sight produces an effective obscuration which is greyer than the 'standard' extinction curves.

While it is generally agreed that galaxies, at least the late Hubble types, contain dust, less agreement exists on how effective the dust is in obscuring the emerging light (e.g., the Cardiff Meeting, Davies & Burstein 1995). What makes dust elusive in galaxies is the lack of obvious emission/absorption features, the potential confusion between dust reddening and the ageing of the stellar population, and the grey 'net' obscuration often produced by the combination of dust scattering and geometry (Witt et al. 1992). Because of these reasons, indirect methods must be usually employed to determine the opacity of a galaxy. Multiwavelength observations to characterize selective obscuration (Peletier et al. 1994, Bosma et al. 1992, CKS94, Calzetti 1997, C97 hereafter), variations of the galaxy opacity with inclination (Giovanelli et al. 1994, Burstein, Willick & Courteau 1995), and extinction of background sources by the foreground galaxy (White, Keel, & Conselice 1996, Berlind et al. 1997, Zaritski 1994, Gonzalez et al. 1997) are among the most common methods.

The central regions and the arms of spiral galaxies are likely to be opaque, with $A_B \approx 1$ or larger, while the interarm regions are generally transparent, with $A_B \approx 0.3$ (White et al. 1996, Giovanelli et al. 1994, Berlind et al. 1997). Dust may be present in the haloes of galaxies ($A_B \approx 0.1$, Zaritsky 1994). Active star formation (SF) is usually associated with strong far-infrared emission from the dust heated by the massive stars (Rieke et al. 1980, Soifer et al. 1987, Helou 1986). The effects of dust in star-forming regions are the result of two competitive processes; on the one side, massive stars are born in the dusty environments of molecular clouds; on the other side, an evolving stellar population tends to blow away or destroy the surrounding dust through supernovae explosions and massive star winds.

Evidence exists for presence of dust at high redshifts. Damped Ly-α Systems (DLAs) around $z \simeq 2$–3 have metallicities around 1/10–1/15 solar and dust/gas around 3–20% of the Milky Way value (Pei, Fall & Bechtold 1991, Pettini et al. 1997a). The DLAs may not be representative of the high redshift galaxy population as a whole, but if so (e.g., Wolfe 1995, Pettini et al. 1997b), the metal abundances at $z=3$ are not primordial, and dust, which

comes with metals, may be a concern (see, however, Pettini & Bowen 1997). In a Universe which is 1/6–1/4 its present age, only a relatively small fraction of gas has been locked up in stars; gas column densities are larger than in the Local Universe and even a small dust/gas ratio can imply a measurable reddening. In the redshift range z$\sim$2.5–3.5, the rest-frame UV is shifted to optical wavelengths; for instance, a spectrum in the wavelength range 4,000–10,000 Å corresponds to the rest-frame range 1,000-2,500 Å of a z=3 galaxy. Therefore, standard ground-based observational techniques are sensitive to the rest-frame UV emission from distant galaxies, namely to a wavelength region potentially heavily impacted by dust reddening.

A "RECIPE" FOR REDDENING

Despite the complications discussed in the previous section, dust reddening at UV and optical wavelengths can be "treated", at least in galaxies and galaxy regions where massive stars dominate the radiation output (CKS94, Kinney et al. 1993, 1994, Calzetti et al. 1996, C97). This includes a wide range of extragalactic objects, from the centrally concentrated starbursts in spirals to the Blue Compact Dwarfs. In regions of SF, the massive star population responsible for the nebular line emission is also responsible for most of the UV radiation. The spectral shape of the UV emission (>1200 Å) is relatively constant over a relatively large range of ages, because we are observing the Rayleigh-Jeans part of the massive stars' spectrum; the non-ionizing photons which make the UV spectrum are less age-sensitive than the ionizing photons (i.e., nebular line emission); the latter disappear before appreciable changes in the UV spectral shape can be observed. If the UV spectrum is fit as F(λ)$\propto \lambda^{\beta}$, the UV index β has values between -2.5 and -2 for a reddening-free, ionizing star population (Leitherer & Heckman 1995, LH95 hereafter). The relation between UV stellar continuum and ionized gas emission has proven crucial for pinning down the selective effects of dust obscuration in star-forming galaxies. Various diagnostics have been constructed from multiwavelength data (Figure 1a and 1b; CKS94 and C97), extending the relation between stellar continuum and nebular emission from the UV to the K band.

Adopting the standard notation:

$$F_{obs}(\lambda) = F_0(\lambda)\ 10^{-0.4 E_s(B-V)\ k(\lambda)}, \quad (1)$$

with $F_{obs}(\lambda)$ and $F_0(\lambda)$ the observed and intrinsic fluxes, respectively, the selective attenuation of the stellar continuum k(λ), normalized to k(B)$-$k(V) = 1, can be expressed as:

$$\begin{aligned} k(\lambda) &= [(1.86 - 0.48/\lambda)/\lambda - 0.1]/\lambda + 1.73 \qquad 0.63\ \mu m \le \lambda \le 1.0\ \mu m \\ &= 2.656\,(-2.156 + 1.509/\lambda - 0.198/\lambda^2 + 0.011/\lambda^3) + 4.88 \\ &\qquad\qquad 0.12\ \mu m \le \lambda < 0.63\ \mu m. \quad (2) \end{aligned}$$

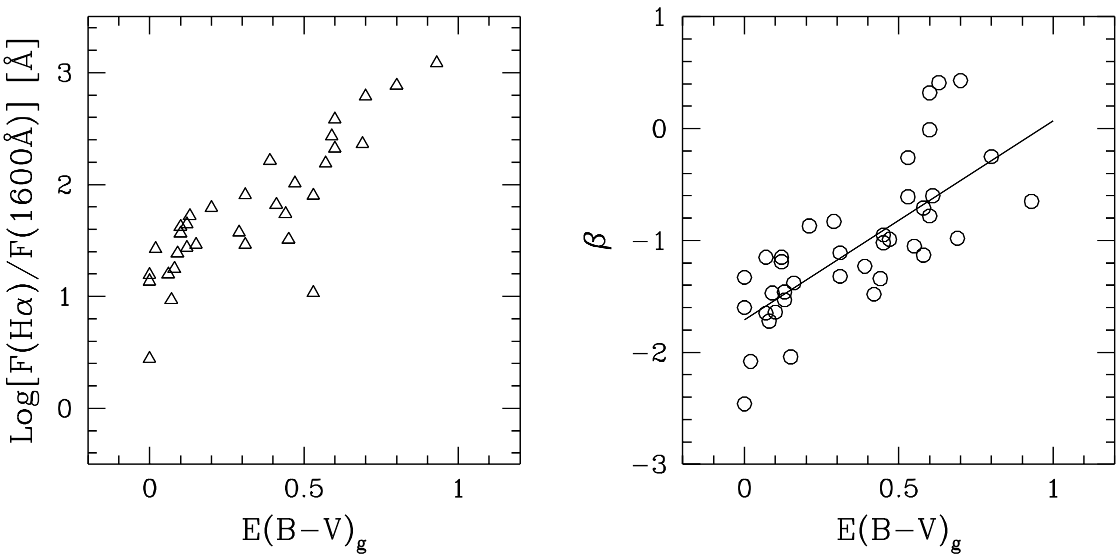

FIGURE 1. a) (left panel). The ratio of Hα to UV emission, observed in a sample of star-forming galaxies, is shown as a function of the color excess of the ionized gas E(B−V)$_g$ (measured from the Balmer line ratio Hα/Hβ). The UV is centered at 1600 Å. If both nebular lines and UV continuum radiation are due to massive stars, the correlation is explainable as an effect of selective reddening at different wavelengths. **b) (right panel)** The UV index β is plotted as a function of E(B−V)$_g$ for the same sample of galaxies. The best linear fit is shown as a continuous line. In a stellar population, the values of β are relatively constant for the range of ages where the nebular hydrogen lines (Hα, Hβ, etc.) are detectable; therefore, the observed correlation between β and E(B−V) is attributable to dust reddening, and not ageing, with the UV spectrum becoming redder for increasing values of the color excess.

The selective attenuation is shown in Figure 2a in comparison with two extinction curves, the Milky Way and the SMC. The comparison is purely illustrative and should not be taken at face value, because the dust attenuation of galaxies is conceptually different from the dust extinction of stars. The latter measures strictly the dimming effect of the dust between the observer and the star, while the former folds in one espression (equation 2) a variety of effects: extinction, scattering, and the geometrical distribution of the dust relative to the emitters. One comparison is, however, licit: the 2175 Å bump, which is a prominent feature of the Milky Way extinction curve, is absent in the attenuation curve. Gordon et al. (1997, see, also, this Conference) have proven that the absence of the feature cannot be explained either with scattering or dust geometry, and must be *intrinsic to the extinction curve* of the ISM in the star-forming galaxies.

Expressions (1) and (2) can be used to derive the intrinsic spectral energy

distribution $F_0(\lambda)$ of the star-forming region, once the effective color excess $E(B-V)_s$ of the stellar continuum is known. Because of the geometrical information folded into the expression of $k(\lambda)$, $E(B-V)_s$ is not a straighforward measure of the total amount of dust between the observer and the source (as in the case of individual stars). The relation between $E(B-V)_s$ and the color excess $E(B-V)_g$ of the ionized gas is:

$$E(B-V)_s = 0.44 E(B-V)_g. \tag{3}$$

Here, the color excess of the ionized gas is derived from the Balmer decrement (or any suitable set of atomic hydrogen emission lines) and the application of a 'standard' extinction curve. The selective extinction of the Milky Way, LMC or SMC curves has similar values at optical wavelengths (Fitzpatrick 1986), so any of these curves can be used for the ionized gas. In addition, a foreground dust distribution appears to work well for the gas when moderate extinctions, $E(B-V)_g \approx 0.1$–1, are present.

Regions of active SF may be inhospitable to dust; supernovae explosions and massive star winds generate shock waves and, possibly, mass outflows (Heckman et al. 1990). Shocks and outflows likely destroy or remove the dust from inside the region; only the external (foreground) dust survives (Calzetti et al. 1996), accounting for the observed gas reddening geometry. This simple interpretation does not account, however, for Equation (3): stars are on average a factor 2 less reddened than the ionized gas (Fanelli et al. 1988, CKS94). The factor 2 difference in reddening implies that the covering factor of the dust is larger for the gas than for the stars (C97). Indeed, while the nebular emission requires the presence of the ionizing stars, the UV and optical stellar continuum is contributed also by non-ionizing stars. Ionizing stars are short-lived and remain relatively close to their (dusty) place of birth during their entire lifetime, while the long-lived non-ionizing stars have time to 'diffuse' into regions of lower dust density. If this is the case, stars and gas will not occupy the same regions (Calzetti et al. 1997), and stellar continuum and nebular emission should be largely uncorrelated. Why then does the reddening of the stellar continuum correlate with the reddening of the ionized gas, as implied by Figure 1? For both the correlation and Equation (3) to be valid, the ageing and diffusion of the stars must be compensated by the production of new massive stars. In other words, the SF event must have a finite duration and cannot be instantaneous. A lower limit to the SF duration can be placed by remembering that the crossing time of a region of $\sim$500 pc is about 50 Myr for a star with v=10 km/s.

Whichever the interpretation, expressions (2) and (3) are purely empirical results, and are independent of any assumption on the geometry of the dust distribution and on the details of the dust extinction curve. They yield probably the most appropriate reddening corrections for the integrated light of extended star-forming regions (or galaxies, see Figure 2b).

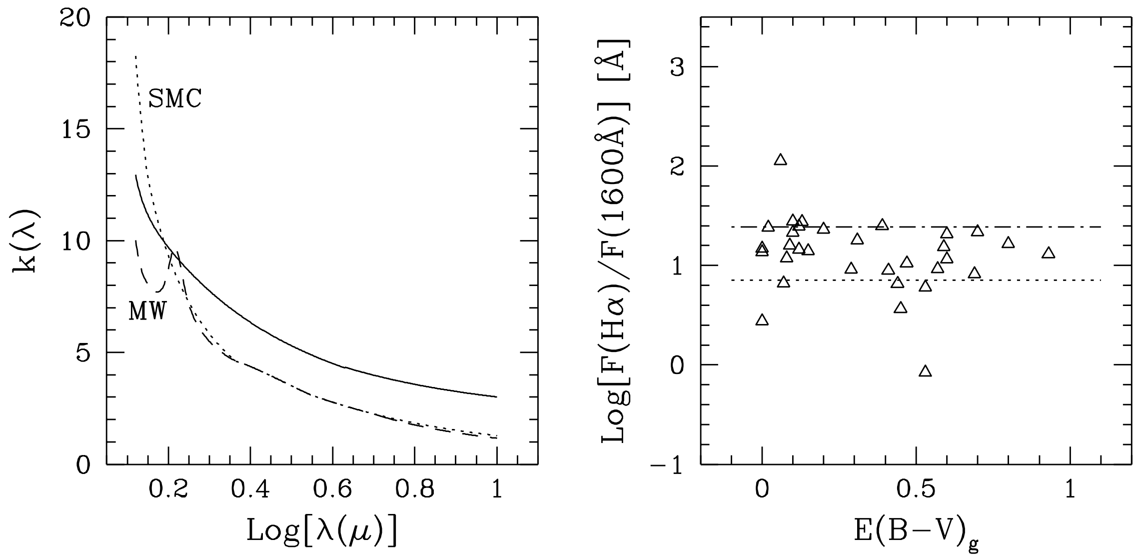

FIGURE 2. a) (left panel). The attenuation curve of Eq.(2) (continuous line) is compared with the diffuse ISM extinction curves of the Milky Way and the SMC (dashed and dotted line, respectively). The attenuation is normalized to k(B)−k(V) = 1. The most prominent feature of the Milky Way curve, the 2175 Å bump, is absent in the attenuation curve. **b) (right panel)** The Hα/UV emission for the same galaxies of Figure 1a is shown after correcting the UV emission for dust attenuation using Eqs.(2) and (3) and E(B−V)$_g$ from the Balmer decrement. The Hα emission is corrected using the Balmer decrement and the Milky Way extinction curve. The two horizontal lines represent the range of expected values for Hα/UV for stellar populations undergoing continuous star formation in the two extreme cases of 0.1–100 M$_\odot$ and 0.1–30 M$_\odot$ Salpeter Initial Mass Function (top and bottom line, respectively). Eq.(2) does recover the UV emission expected for the observed Hα emission.

DISTANT GALAXIES

The recently discovered galaxy population at z$\sim$3 (Steidel et al. 1996) and the UV-dropouts in the Hubble Deep Field (Williams et al. 1996) have re-opened the debate on the SF and metal production histories of the high-redshift Universe (see Madau et al. 1996). One of the current issues is to understand which fraction of the total high-redshift SF these galaxies represent (e.g., Pettini, this Conference, Dickinson, 1997; Madau, 1997). Here, the potential impact of dust reddening on the estimates of the high-redshift SF and metal production rates are briefly discussed (see, also, Meurer et al. 1997, and, for a detailed analysis, Dickinson 1997).

By the nature of the detection criterion (Steidel & Hamilton 1993), all the z$\simeq$3 galaxies have intense UV emission, tracer of recent massive SF (Steidel

et al. 1996, Giavalisco et al. 1996). From the spatial extension of the UV emission (a few kpc, Giavalisco et al. 1996), the galaxies have been forming massive stars for at least 100 Myr and probably more; this is the amount of time required by the 'SF wave' to cross a typical galaxy scale, 1 kpc, if it travels at the sound speed, v≈10 km/s. The spectrum of a dust-free galaxy which is forming stars at a constant rate since T_d=100 Myr has $\beta \sim -2.45$, and, if T_d=1 Gyr, $\beta \sim -2$, with little dependence on the metallicity down to 1/10 solar (LH95, Bruzual & Charlot 1996, C97). However, the UV indices measured in the high-z galaxies are redder than these values; the observed *average* UV index of the distant galaxies is $\beta \simeq -1.1$ (Meurer et al. 1997). Taking into account corrections for the Lyman Forest absorption, the galaxies UV spectral energy distributions become slightly bluer, $\beta \simeq -1.2$ to -1.5 (cf. Dickinson 1997), but still too red to be compatible with on-going constant-rate (or slowly decreasing) SF. To reconcile the observed *average* UV index with the expectation for a star-forming galaxy, three possible scenarios (or a combination thereof) can be invoked: 1) the massive end of the Initial Mass Function of the z=3 galaxies is steeper than the present-day IMF; 2) the z=3 galaxies are 'aged star-forming galaxies': the SF happened in the past and massive stars are no longer being formed in large quantities; ageing reddens the UV index of a stellar population; 3) the UV emission of the z=3 galaxies is reddened by dust. Ageing and reddening are particularly important, because both scenarios suggest that the SF and metal production rates inferred from the observed UV emission of the high-z galaxies are underestimates of the global SF and metal production rates.

• *The IMF.* There is increasing evidence that in local starbursts the slope and high-mass cut-off of the IMF above 5–10 $M_\odot$ is independent of the environment (Massey et al. 1995, Stasińska & Leitherer 1996). Invoking a different IMF between the high redshift and the present-day galaxies thus requires an explanation of why the IMF has changed with time. In this regard, it should be remembered that the metallicity of high-z Damped Ly-α Systems is not drastically lower than the values observed today in Blue Compact Dwarf galaxies. The shape of the IMF is thus unlikely to have changed from z∼3 to the present, though the issue is still open.

• *Ageing.* The average high-z galaxy is assumed to be a dust-free ageing stellar population. Let's assume the stellar population was generated in a constant-SFR, star-forming episode of duration T_d. After T_d years, the SF stops, and the stellar population is left ageing for T_a years; the "average" galaxy is observed at T_a to account for the red UV index. For T_d=100 Myr, a time $T_a \simeq$150 Myr must lapse before $\beta \simeq -1.2$. At this stage, the UV flux around 1500 A is about f=55 times lower than the value at t≤100 Myr. A T_d=1 Gyr star-forming population would need $T_a \simeq$20–50 Myr to reach $\beta \simeq -1.2$. In this case, the decrease in UV flux relative to the peak is about a factor f∼4–6. If the observed galaxies are located at z=3 (3.5), the peak of SF (t≤T_d) would occur at z>3.12 (3.7) in an open Universe (H_o=50 Mpc/km/s

and q_o=0.0) and at z>3.25 (3.9) in a flat Universe (q_o=0.5). This peak has not been observed (e.g., Madau et al. 1996), although the incompleteness of the samples may play a large role here; of course, the redshift of the peak can be pushed to higher values if the SF doesn't interrupt abruptly after T_d (as in our simplified model), but is a decreasing function of time.

• *Reddening.* If the *average* z=3 galaxy can be described by a 1 Gyr old stellar population undergoing SF at a constant rate, an effective color excess $E(B-V)_s \simeq 0.15$ is needed to change the UV index from −2 to −1.2. This modest color excess implies a UV attenuation $A_{(1600\,\mathring{A})} \simeq 1.65$. The intrinsic UV emission, and corresponding SFR, is then underestimated on *average* by a factor f∼5. Any stellar population younger than 1 Gyr will have bluer intrinsic UV spectra, and will imply larger reddening corrections (cf. Meurer et al. 1997).

A simple argument can be used to infer that the amount of metals produced in the z=3 galaxies by the observed SF event are comparable for the ageing and the reddening scenarios. The injection of metals into the ISM is proportional to the total number of massive stars produced. If the IMF is the same in the two scenarios, the number of massive stars generated by the SF event is proportional to the observed SFR, sfr_{obs}, to the factor f by which sfr_{obs} underestimates the peak SFR, and to the duration of the burst, T_d. The quantity sfr_{obs} comes from the observed UV emission and is the same in both scenarios. In the ageing case, $f \times T_d = 55\times100$ Myr and 4×1 Gyr, respectively; in the reddening case, $f \times T_d = 5\times1$ Gyr. Therefore, both scenarios predict the same amount of metals produced at z∼3–4 over the lifetime of the SF event. More sophisticated models for the stellar populations and evolution of the high-z galaxies would probably still give numbers in this ballpark. Metal production thus does not appear to be a good discriminant between ageing and reddening in the high-z galaxies.

Both reddening and ageing predict that the observed UV emission from the distant galaxies underestimates the peak SFR; there is an important difference between the two, though: in the first case, the underestimated quantity is the 'current SFR' at z∼3; in the second case, the quantity is the 'recent past SFR' a redshift beyond 3. Probably the most direct way to prove whether the high-z *average* UV spectra are red because of dust obscuration or ageing will be to measure the intensity of the hydrogen Balmer lines: these are more directly related to the number of ionizing photons than the UV emission, and can help constraining the average age of the massive star population.

CONCLUSIONS

We have seen that, despite the instrinsic complexity of the dust opacity in external galaxies, in certain cases the problem of dust obscuration is treatable. A 'recipe', under the name of 'attenuation curve', is available for the reddening

correction of the integrated light from star-forming regions. The strength of the starburst attenuation curve is that its derivation is purely empirical and does not rely on models. The curve is therefore applicable at least to the class of objects it has been derived from: the central star-forming regions of galaxies.

One of the open problems is understanding the limits of applicability of the curve. In the case of isolated HII regions, where the SF processes are less energetic than in the case of starbursts, the dust can survive the less harsh environment and be uniformly distributed with the stars. For this reason, the attenuation curve will not be generally applicable to HII regions. Similar arguments can be used in the case of 'quiescent' galaxies.

Other open problems are the meaning of Equation (3), namely, the discrepancy in global attenuation between stars and gas though they are still correlated, and the physical meaning, if any, of the effective color excess $E(B-V)_s$ of the stellar continuum. These and other issues will require further investigation.

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